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The Future Challenge for Aeropropulsion

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THE FUTURE CHALLENGE FOR AEROPROPULSION

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Abstract

NASA's research in aeropropulsion is focused on improving the efficiency, capability, and environmental compatibility for all classes of future aircraft. The development of innovative concepts, physical understanding and theoretical, experimental and computational tools provide the knowledge base for continued propulsion system advances. Key fundamental enabling technologies include advances in internal fluid mechanics, structures, light-weight high-strength composite materials, and advanced sensors and controls. Recent emphasis has been on the development of advanced computational tools in internal fluid mechanics, structural mechanics, reacting flows, and computational chemistry. The improved computational capability and advanced materials are being used to develop advanced propulsion system component technology, for example, lightweight turbomachinery with improved efficiency, combustor systems that retain high combustion efficiency while reducing harmful emissions, and low noise, lightweight exhaust systems. The fundamental knowledge base and component technology form the physical and analytical foundation for focused research activities. For subsonic transport applications, very high bypass ratio turbofans with increased engine pressure ratio are being investigated to

increase fuel efficiency and reduce airport noise levels. In a joint supersonic cruise propulsion program with industry, the critical environmental concerns of emissions and community noise are being addressed. NASA is also providing key technologies for the National Aerospaceplane, and is studying propulsion systems that provide the capability for aircraft to accelerate to and cruise in the Mach 4-6 speed range. The combination of fundamental, component and focused technology development underway at NASA will make possible dramatic advances in aeropropulsion efficiency and environmental compatibility for future aeronautical vehicles.

Introduction

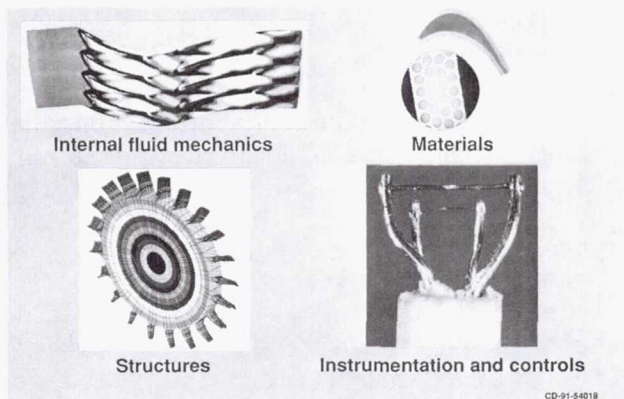
NASA is pioneering a broad fundamental knowledge and technology base that is critical to the design of advanced aeronautical systems, both civil and military. We are pursuing the development of innovative concepts, the physical understanding and the theoretical, experimental and computational tools that provide the foundation to keep the United States at the forefront of aviation. This knowledge base forms the physical and analytical foundation for NASA's current and future focused research activities as well as the understanding required for concept breakthroughs. The expertise of its researchers and its

experimental and computational facilities place NASA in a position to perform the broad range of disciplinary and applied research needed in the future.

Critical Disciplines

The basic aeropropulsion discipline technologies include internal fluid mechanics, materials, structures, and instrumentation and controls. An advanced set of computational tools are

Basic Discipline Technologies



being developed and validated with measurement systems that do not intrude on the results of the test (Ref 1). NASA is advancing the state-of-art in each of these disciplines, with an emphasis on materials and computational tools. Materials research for lightweight, high strength capabilities is focused on polymeric, intermetallic and ceramic matrix composites. NASA is advancing computational capability in fluids and structures with improved methods that reduce the time required for complex calculations, innovative ways to rapidly describe the shape of new configurations, and advanced modeling to improve the physical accuracy of the analysis. Research has been initiated to bring the computational capability of individual disciplines together into a multidisciplinary capability that will simultaneously simulate the flows, structures and controls.

Internal Fluid Mechanics

A major effort in internal computational fluid mechanics is simulating the flow in high speed fans and compressors. An example (ref 2) of such a numerical experiment is presented in the adjacent

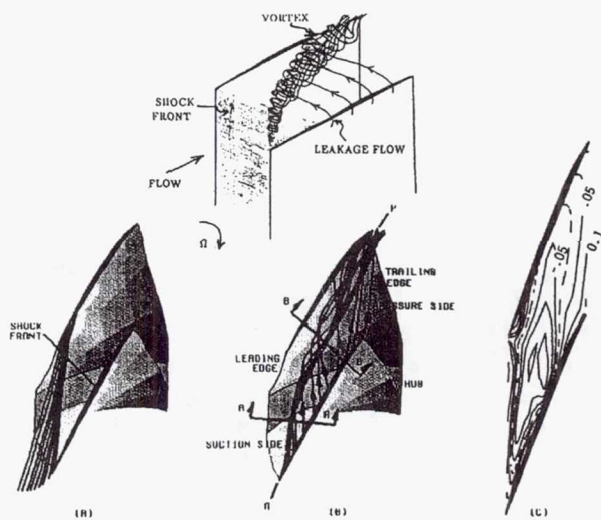


figure. The upper portion of the figure illustrates the formation of the leakage vortex and its encounter with the in-passage shock at the near stall operating condition. The views in all portions of the figure are from the shroud looking in toward the hub. The lower left portion of the figure shows the streamlines at 99% span as defined by particle paths originating upstream of the rotor at a radial surface above the rotor tip. The streamline originating from the leading edge divides the upstream flow from that which came through the clearance. The shock location is also shown in this figure. The lower center portion of the figure shows the paths of fluid particles released in the clearance region over the suction surface. The line O-P shows the trajectory of the vortex across the passage. The formation of the leakage vortex is evident. The vortex cross section increases markedly in size as it traverses the shock. This vortex growth is responsi-

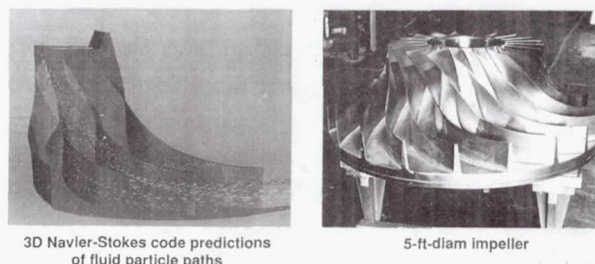
ble for the sharp increase in endwall blockage as stall is approached. The lower right portion of the figure is a contour plot of the axial velocity normalized with respect to the tip wheel speed on an axisymmetric surface of revolution at 99 percent of span. The dashed contour corresponds to zero axial velocity. The contours within the zero contour are negative while those without are positive. Notice that the region of negative velocity extends across the entire passage. As the flow is further reduced towards stall, the negative velocity area would extend forward of the rotor inlet plane, indicating the spilling of low energy flow into this region. This numerical experiment demonstrated how the clearance over the forward portion of the fan blade controls the flow processes leading to stall.

To validate codes similar to the one used in the above numerical experiment, NASA has developed the Integrated CFD and Experiment (ICE) Program illustrated in the adjacent figure. The objective

reduce and display measurements from advanced instrumentation systems in real time during the experiment. The ICE also involves storing CFD results and experimental data as independent data bases on a common mass storage system, then retrieving both CFD and experimental results and displaying them through a common graphics interface for further off-line comparison and analysis.

A recent NASA program demonstrating the effort to validate codes is the Low Speed Centrifugal Compressor Research Program. It couples the analysis of centrifugal compressor flow fields using 3D Navier-Stokes codes with experimental measurements acquired in the unique large-size, low-speed centrifugal compressor impeller shown in the adjacent

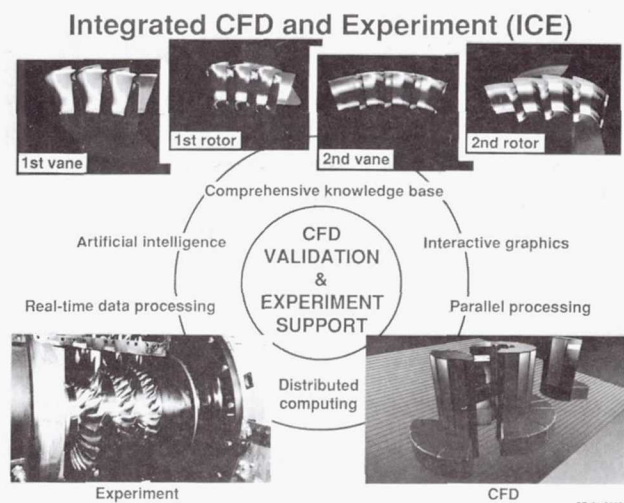
Low Speed Centrifugal Compressor Research



3D Navier-Stokes code predictions of fluid particle paths

5-ft-diam impeller

figure. The results of a numerical prediction of the impeller flow field is shown on the left of the figure. Fluid particles in the blade boundary layer are being tagged from hub to tip near the blade leading edge on both the blade pressure and suction surfaces and then followed as they proceed toward the impeller exit. The numerical result indicates that this fluid is being driven to the tip of the blade, then passes through the tip clearance gap, and accumulates in a vortex-like structure which exits the impeller near the pressure-surface side of the blade passage. Such results improve our understanding of the complex impeller flow physics and serve as a guide in planning the location and extent of detailed laser anemometer flow

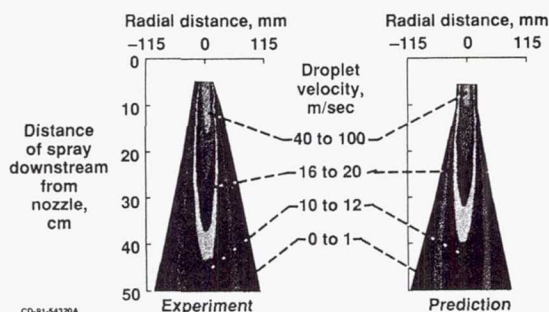


is to tightly couple the experimental and computational research efforts. This will be accomplished by utilizing parallel processors to reduce the cost of CFD calculations, and combine their capability with graphics to rapidly

field surveys.

Combustors with their complex multiple phase flows, turbulence, and chemical reactions, are a target for future analysis. The CFD research emphasizes the development of efficient and accurate algorithms and codes, as well as validation of methods and modelling (turbulence and kinetics) for reacting flows. The following figure compares experiment with numerical prediction of axial droplet velocity for a non-reacting spray. The experiment consisted of an air as-

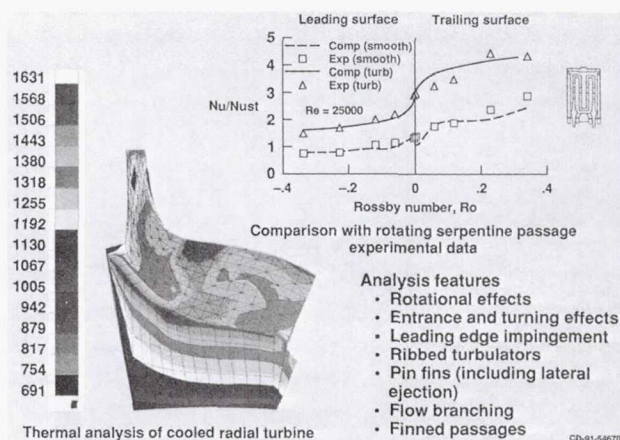
Mean Axial Droplet Velocity (25 μ m) for Nonreacting Spray



sisted atomizer spraying vertically downward into a stagnant environment. Velocity measurements were made with a two-component Phase/Doppler particle analyzer and were obtained across the entire spray. The computer model utilized for the predictions is parabolic with Lagrangian particle tracking, includes source terms for momentum exchange between droplets and the gas phase, and considers turbulent dispersion of the droplets. Agreement is considered to be reasonable.

Heat transfer is another area where CFD is just beginning to produce practical results. Turbine cooling passage heat transfer is critical to turbine life prediction, and is illustrated in the figure below. The one-dimensional analysis includes the many physical and geometric turbine passage features listed on the figure. It was applied to the rotating serpentine passage illustrated to the right of the plot, and provided

Turbine Coolant Passage Heat Transfer Analyses

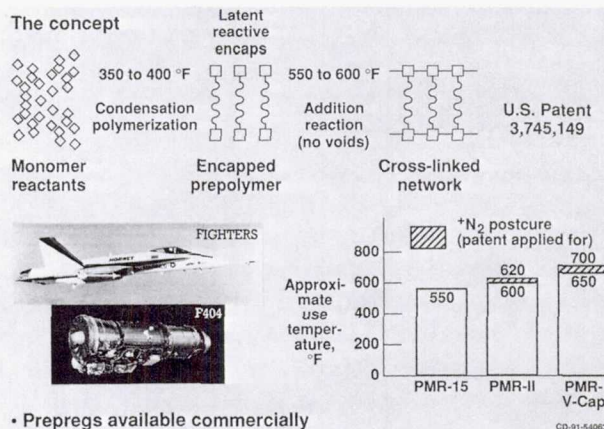


excellent agreement with the measured data for both smooth and rough cooling surfaces. The analysis was also used to predict the temperature distribution of a cooled radial turbine, which is shown in the figure. Results from the cooled turbine testing will be used to further validate the analysis.

Materials

In its Aeropropulsion Materials Program, NASA is synthesizing new compositions, optimizing the processes for material formation, and developing basic material characteristics and property data. This work is focused on polymeric, intermetallic and ceramic matrix composites. This is illustrated in the figure below

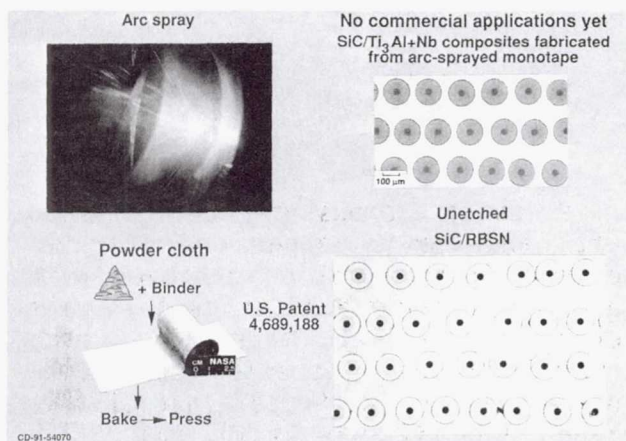
PMR Family of PMC's for 500 to 700⁺ °F



by a two-step polymerization of monomeric reactants (PMR) process which was developed by Lewis researchers. This process allowed liquid and gas reaction products to escape the composite structure prior to final cross-linking. Through collaboration with the U. S. Navy and General Electric Company, PMR-15 engine ducts are flying in the F-404 engines that power the Navy's F-18 Hornet fighters. These ducts save about 30 percent of the total weight and cost over the previous titanium duct. Recently, Lewis scientists have increased polymer molecular weight, added more thermally stable end-caps, and by a nitrogen post cure, substantially raised the glass transition temperature to provide higher ultimate use temperatures.

Numerous advanced composite fabrication processes have been also developed by NASA scientists. As seen in the adjacent

Composite Fabrication



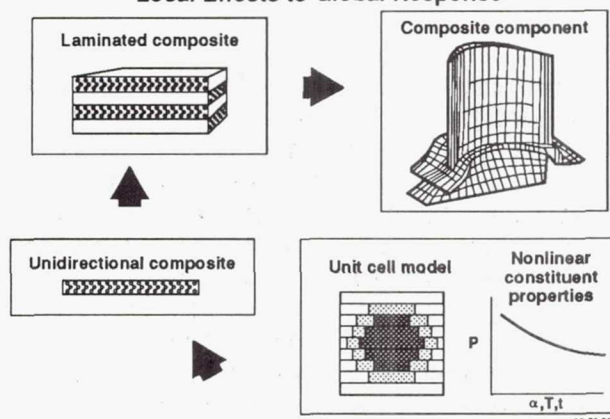
cent figure, the NASA arc spray method and the "powder cloth" approach have been used to make intermetallic and ceramic monotapes. Such tapes can then be angle plied, laid up, and hot pressed or HIPed to the final desired density and near-net shape.

Structures

The NASA Aeropropulsion Structures Pro-

gram includes probabilistic analysis and design, nonlinear material properties, symbolic logic, composite micromechanics, aeroelasticity, fatigue and fracture of composite structures, life prediction and aspects of nondestructive evaluation. These programs, which for the most part are analytically based, are experimentally verified and are used to develop computer codes necessary for the design of complex engine structures. Mechanical performance and structural integrity of high-temperature metal matrix and ceramic materials is governed by local behavior at the level of the composite constituents, i.e., fiber and matrix. Hence, in the analysis and design of aircraft engine components which are ultimately to be fabricated from these composite materials, it is necessary to understand and model the local behavior of the material over the component volume and relate its effects to global structural performance as shown in the adjacent figure. The crit-

Composite Structures Simulation Relates Local Effects to Global Response

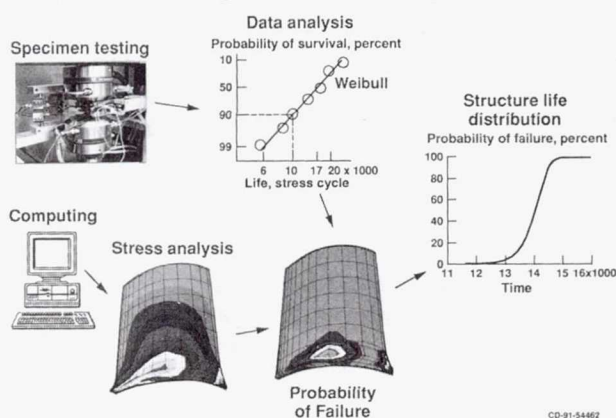


ical local behavior is governed by such factors as imperfect bonding at the fiber-matrix interface, the progressive nature of microcracking, and nonlinear dependencies of constituent properties over the range of conditions in which the engine operates. We integrate constituent material models, cumulative damage models, composite mechanics, and global finite-element structural analysis to analyze this problem. With this

capability, local effects on overall component behavior can be resolved and yet adequate efficiency achieved to be practical for realistic engine component applications.

Using probabilistic methodology, the component design survivability can be mapped by incorporating finite-element analysis and probabilistic material properties. As shown in the adjacent

Life Prediction Methods Bridge Gap Between Specimen Testing and Full-Scale Engine Structure

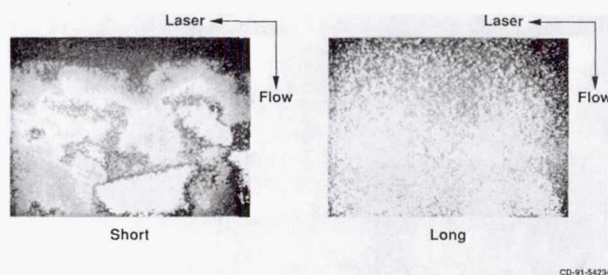


figure, the method evaluates design parameters through direct comparisons of component survivability expressed in terms of Weibull parameters. The method allows the use of statistical data obtained from laboratory coupon testing under environmental conditions to be integrated into life and risk analysis of full-scale engine structures. It is possible through an interactive design process to minimize the risk of failure for a given operating time or, conversely, to design for a finite life for a defined risk. When Weibull parameters and the stress-life exponent of the material are unknown, it is permissible to assume these values in order to obtain a qualitative, if not quantitative, evaluation of a structural design. We are currently applying these methods to full-scale structures such as turbine blades and disks where full-scale component data exist.

Instrumentation and Controls

The NASA Aeropropulsion Research has a long history of investigation in advanced research instrumentation and propulsion controls. Research instrumentation is focused on minimally intrusive contact sensors and nonintrusive optical measurement systems compatible with the increasingly hostile environment of modern engines. A prototype nonintrusive optical flow diagnostic system based on planar laser-induced fluorescence has recently been developed for NASP propulsion research. Measurements of the exhaust of two versions of a scramjet combustor are shown in the figure below. These represent the OH concentration

Planar Laser-Induced Fluorescence Measurements of OH Concentration in a Scramjet Combustor

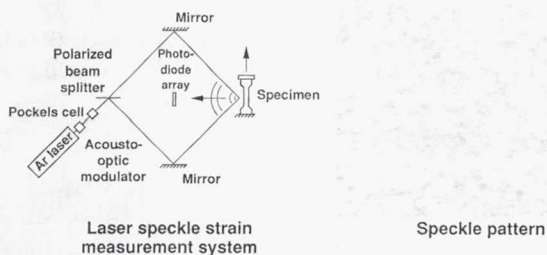


for a short combustor configuration (left) and for a longer one (right). The more uniform mixing achieved with the longer combustor is evident in this picture. Similar maps have been achieved for other species concentrations as well as for temperature distribution. Quantitative as well as qualitative data will be obtained from this system.

Another remote optical measurement system is the use of speckle interferometry for strain measurement. It is aimed at those situations where the temperature is beyond the capability of strain gage alloys and/or where the surface strain is large enough to enter the plastic region. The technique depends on the fact that the speckle pattern produced

by impingement of laser light on a surface is caused by slight irregularities in the surface. This speckle pattern thus moves when the surface is strained. Electronic photographs of this pattern are taken before and after straining, and are then processed to track the speckles; thereby measuring the strain. The left illustration in the figure

Speckle Interferometry for Remote Strain Measurements



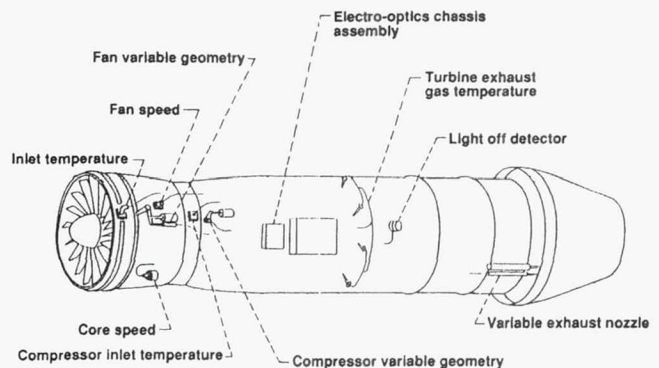
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shows the system schematically. The speckle pattern (example on right) is photographed before and after strain from two different directions. Processing of all four images allows the strain to be separated from any rigid body motion which might have occurred along with the strain.

Because optical fibers are dielectric, problems with the effects of electromagnetic interference, electromagnetic pulse, and lightning are eliminated. Also, it is expected that replacing control-system electrical wiring with optical fibers will result in weight and volume savings, as well. The high bandwidth capability is advantageous for bus lines and offers the potential for all avionics data to be transmitted over a single line. To develop and demonstrate fly-by-light control-system technology, NASA has undertaken the Fiber-Optic Control System Integration (FOCSI) program. Phase I, initiated in 1985 and completed in 1986, was a NASA-DOD effort aimed at the design of a fiber-optic propulsion/flight control system. Phase

II, a NASA-Navy effort currently in progress, will provide the system design, subcomponent and system development, and system ground tests. Phase III, flight demonstration, has also been initiated and will culminate in full FOCSI system flight tests. The FOCSI propulsion system configuration is shown

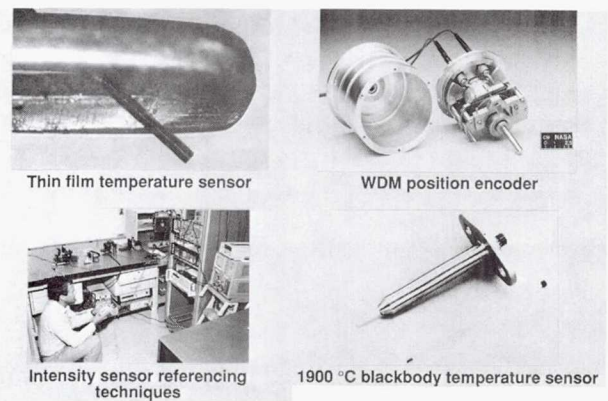
FOCSI Propulsion System Configuration Propulsion System Prime-General Electric Aircraft Engines



in the adjacent figure. The full complement of FOCSI propulsion system sensors and the electro-optics chassis assembly are shown as they will be mounted on the engine.

Current in-house and sponsored research efforts illustrated in the adjacent figure vary from the development of

Fiber-Optic Sensors Research



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near-term flight prototype control sensor systems through far-term investigation of innovative sensor/sensor-system concepts and includes work in;

- Flight prototype aircraft control sensor systems
- On-engine demonstrations of sensor systems
- Laboratory demonstration/testing of new sensor concepts
- Improved sensor referencing/signal processing techniques
- Integrated optics/microfabrication techniques
- Electro-optic component research

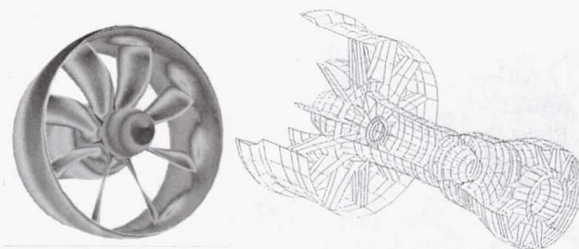
The overall goal is to develop miniature, rugged, passive, optical sensor systems which operate reliably in the aerospace environment. Shown in the figure are (clockwise from top left) a novel thin film temperature sensor, a wavelength division multiplexed optical encoder, a blackbody temperature sensor, and laboratory work to improve optical intensity, sensor accuracy, and precision.

Multidisciplinary Research

Implementing a new technology in aerospace propulsion systems is becoming prohibitively expensive. One of the major contributors to the high cost is the need to perform many large-scale system tests. Extensive testing is used to capture the complex interactions among the multiple disciplines and the multiple components inherent in complex systems. The object of NASA work on a Numerical Propulsion System Simulation (NPSS) Program is to provide insight into these complex interactions through computational simulations. The tremendous progress taking place in computational engineering and rapid increase in computing power expected through parallel processing make this concept feasible within the near future. However, it is critical that the framework for such simulations be put in place now to serve as a focal point for the continued developments in computational engineering and computing hardware and software. The NPSS concept will provide that framework.

Implementation of NPSS requires a hierarchy of codes and models to be in place to provide a wide range of capabilities from detailed three-dimensional, transient analyses of components to time- and space-filtered analyses of the subsystems and systems. Modeling approaches will be developed for communicating information from a detailed analysis to a filtered analysis. Additional research will be required to understand the mechanisms by which phenomena on different length and time scales communicate. Research is already underway in computational fluid dynamics and structural mechanics to develop this modeling approach and will be extended to consider processes and scales appropriate for the entire propulsion system. Illustrated on the left of the adjacent figure

Single-Discipline Modeling



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ure is the Adamczyk (ref 2) average-passage formulation which will be the fluid dynamic simulation model that will serve as the basis for the integrated system model. The average passage model, which has been developed for multistage turbomachinery analysis, is based on the filtered forms of the Navier-Stokes and energy equations. This model was designed to resolve only the temporal and spatial scales that have a direct effect on the relevant physical processes. The structures modeling, illustrated on the right, will be aimed at developing a comparable computational capability that will provide a means to traverse multi-

ple scales of spatial resolution with a minimum number of variables at each level. In this way an analysis can proceed from a blade to a rotor to an engine core to the complete engine. The resulting system will have a minimum number of degrees of freedom consistent within the objectives of the analysis and will minimize the computational requirements.

Vehicle Focused Research

To assure the practical application of the technology developed under the research on basic disciplines, NASA focuses much of its research on vehicle focused applications. These applications include subsonic and supersonic transport aircraft, high performance military aircraft, and hypersonic/transatmospheric vehicles. Examples of this research follow for subsonic and supersonic transport aircraft.

Subsonic Transport Research

Propulsion technology for subsonic transports is focused in two main areas: (1) low-noise ultra-high-bypass (UHB)

Subsonic Transport Propulsion Research

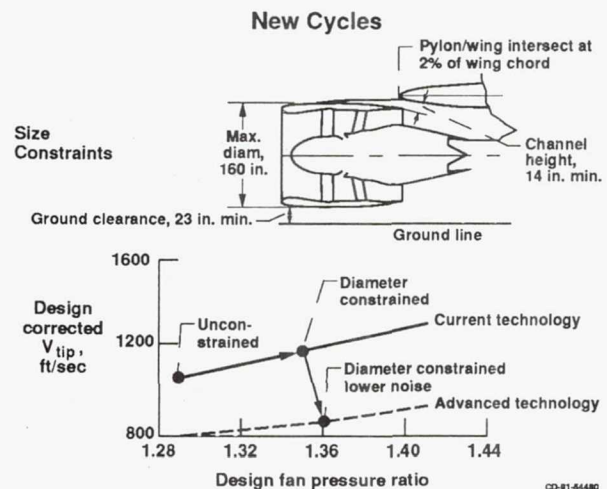


- Focused Technologies:
- Ultra-high-bypass ratio cycles
 - Ducted props/fans
 - Low noise
 - High-efficiency core

ratio cycles and (2) high-efficiency cores. Previous work demonstrated the technology for fuel-efficient, unducted, advanced turboprops and that effort is concluding. Unducted ultra-high-bypass ratio engines are subject to total thrust limits due to diameter con-

straints for under-the-wing installations. Thus, current work emphasizes ducted prop/fan configurations suitable for large wide-body aircraft powered by two large-thrust engines mounted under the wing as shown in the figure above.

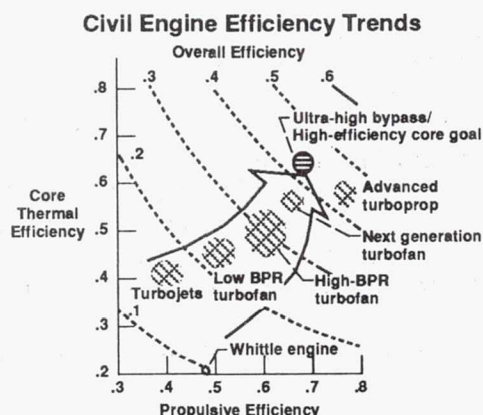
The need for larger thrust engines for twin-engine, long-range aircraft is constrained by engine diameter. Further, to reduce the fan noise level, the most effective techniques are to reduce fan tip speed and introduce blade sweep developed in the Advanced Turboprop Program. Designers are therefore presented the task of reducing fan tip speed while increasing fan pressure ratio. Shown in the adjacent figure is



a result from a cycle study to identify future technology requirements. The desired changes in fan tip speed and pressure ratio are significant challenges and will require advanced technology to operate at these highly loaded conditions with acceptable levels of fan surge margin. To fully understand the performance and noise of such a configuration will require an integrated three dimensional analysis of the interaction of the fan, stator, and nacelle.

High-efficiency core investigations center around increasing thermal efficiency by pushing core pressure ratios

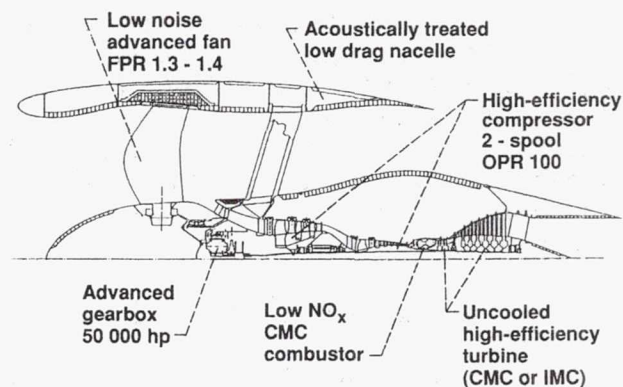
and temperatures higher. The overall goal is to maximize engine efficiency subject to the environmental constraints of aircraft noise rules and emission limits. As seen in the adjacent figure, large gains in turbine engine overall



efficiency have been made since the first turbojets were introduced. Recent advances such as high-bypass turbofans and the advanced turboprop have resulted largely in improvements in propulsive efficiency. The goal of the current set of NASA/Industry studies was to emphasize the core in order to investigate the potential of improving the thermal efficiency over that of the next generation turbofan. A shift in the efficiency trend is shown by the arrow curving to a more vertical direction in the figure.

A typical 100:1 overall pressure ratio engine that resulted from the studies, shown in the figure below, consists of a two-spool geared configuration with a bypass ratio of 20 to 25. The resulting fan pressure ratios are 1.3 to 1.4. Low drag nacelles are required to minimize the losses associated the high bypass ratios. Efficiency improvements are needed in both the compressor and the turbine to enable thermal efficiency improvements at the high pressure ratio. Advanced materials such as ceramic matrix composites (CMC) and intermetallic matrix composites (IMC) are used exten-

In-Line Engine Configuration



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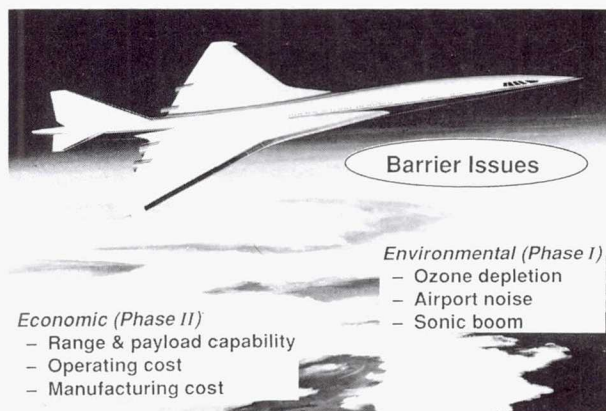
sively throughout the hot section of the engine to reduce or eliminate cooling flow requirements. Since the low-noise fan must be geared to the high-efficiency turbine, advanced gearbox technology will be needed to achieve the required transmission power of about 50,000 horsepower. As a result of the high overall pressure ratio, the combustor entrance pressure and temperature are very high. This would result in NO_x formations exceeding current levels with current technology combustors. Therefore, low NO_x combustor technology must be developed for the very small combustors in this type of engine.

High Speed Research Program

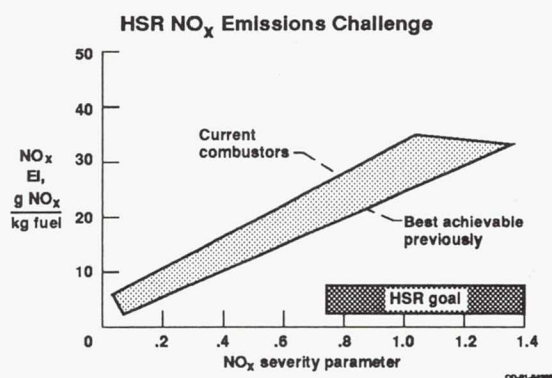
The NASA Phase I High-Speed Research Program (HSRP), illustrated in the figure below, emphasizes solutions to the critical environmental barrier issues associated with any future HSCT aircraft. Two of these barrier issues - atmospheric ozone depletion and community noise are primarily propulsion issues. The critical economical viability issues will be the emphasis of the proposed future effort.

To meet the requirement to minimize atmospheric ozone depletion will require

High-Speed Research Program



the NO_x emissions challenge illustrated in the adjacent figure. Initial two-

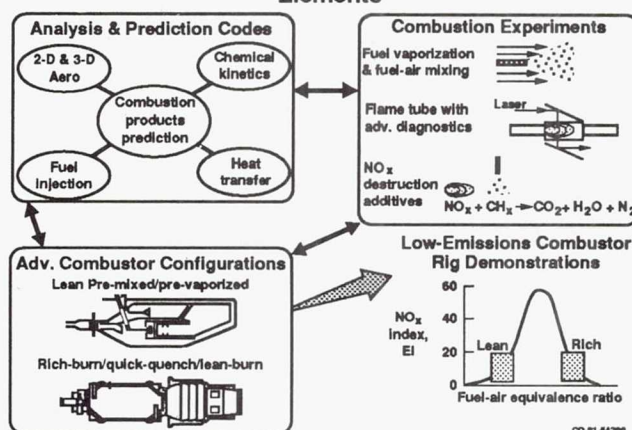


dimensional atmospheric impact studies suggest that ultra low NO_x combustor technology will be required if no adverse impact on the ozone layer is to occur. The standard term for expressing NO_x emissions levels is emissions index (EI), defined as the ratio of the grams of equivalent NO₂ produced to the kilograms of fuel burned. The figure presents the emissions parameter as a function of a severity parameter which increases with increased combustor pressure and temperature levels. The ultra-low NO_x levels represented by the HSR goal would have EI's in the range of 3 to 8. The top of the open band represents current combustor performance, and the lower bound of the band represents

performance levels demonstrated in the NASA/Industry Experimental Clean Combustor Program. Obviously, new approaches to reducing combustor emissions are required.

The major elements of the low emissions combustor technology portion of the HSRP are shown in the figure below. Initial-

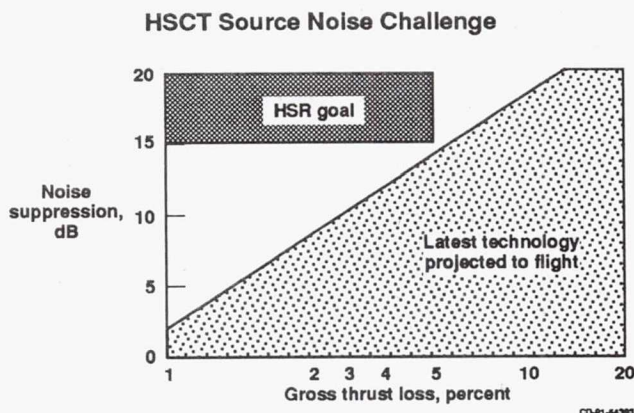
Low-Emissions Combustor Technology Elements



ly, emphasis will be on the development and validation of the computer analyses to predict the details of the combustion process within candidate combustor configurations. Also, laboratory experiments will be conducted to evaluate candidate combustor configurations and candidate low-NO_x combustion approaches. These laboratory tests will be used in conjunction with advanced diagnostics to develop a comprehensive combustion code validation data base. These experimental data bases and the analytical prediction codes will form the basis for conceptual design of candidate low-nox combustors. The deliverable of this element of HSRP will be the demonstration of ultra-low-NO_x combustor configurations in rig demonstrations. Currently, two combustor concepts appear to hold promise for meeting the HSRP emissions goal: the lean-premixed-prevaporized (LPP) and the rich-burn/quick-quench/lean-burn RQL.

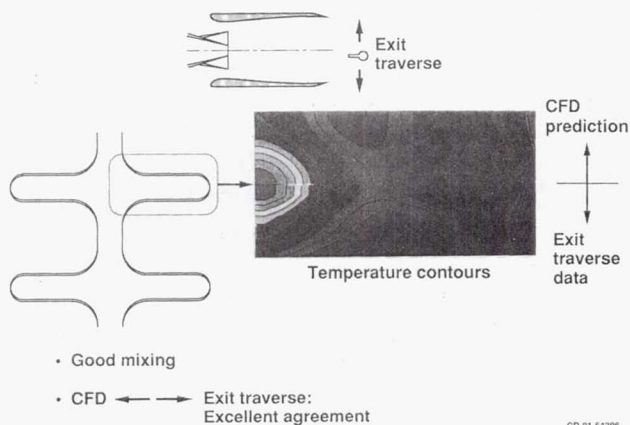
The HSCT noise challenge is illustrated

in the adjacent figure. The jet exhaust



noise levels at takeoff and landing conditions must be reduced by 15 to 20 DB relative to reference conic nozzle levels before any future HSCT can hope to meet FAA noise regulation limits. At the same time, the nozzle aerodynamic performance levels must be kept high if vehicle overall mission performance goals are to be met. This combined acoustic-aerodynamic challenge is often expressed as a ratio of decibel noise reduction to resultant percent thrust loss. For a viable HSCT design this ratio should be in the neighborhood of 4:1. As this figure shows, current technology would yield a nozzle design with a ratio of no better than 2:1.

CFD/Translating Probe Comparison and Mixing



In attempting to meet the FAA noise limits with a HSCT nozzle, CFD codes are being used to analyze the internal mixing of ejector nozzles. The figure above presents a comparison of the temperature profiles from a two-dimensional model test and a Navier-Stokes calculation. The agreement is judged to be excellent, and the results suggest that the CFD computer codes will have a critical role in designing the complex flow field of an HSCT low noise ejector nozzle.

Concluding Remarks

The potential for increased efficiency, higher speeds, and improved environmental compatibility combine to challenge the aeropropulsion manufacturers of the future. NASA is working on developing the tools in the critical discipline areas of internal fluid mechanics, instrumentation and controls, materials, and structures to allow the design of future propulsion systems that meet those challenges. In areas where the future performance goals are in sight, it is demonstrating the application of those tools to future advanced propulsion systems to make the marketing of such a system an attractive opportunity.

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13. ABSTRACT (Maximum 200 words) NASA's research in aeropropulsion is focused on improving the efficiency, capability, and environmental compatibility for all classes of future aircraft. The development of innovative concepts, physical understanding and theoretical, experimental and computational tools provide the knowledge base for continued propulsion system advances. Key fundamental enabling technologies include advances in internal fluid mechanics, structures, light-weight high-strength composite materials, and advanced sensors and controls. Recent emphasis has been on the development of advanced computational tools in internal fluid mechanics, structural mechanics, reacting flows, and computational chemistry. The improved computational capability and advanced materials are being used to develop advanced propulsion system component technology, for example, lightweight turbomachinery with improved efficiency, combustor systems that retain high combustion efficiency while reducing harmful emissions, and low noise, lightweight exhaust systems. The fundamental knowledge base and component technology form the physical and analytical foundation for focused research activities. For subsonic transport applications, very high bypass ratio turbofans with increased engine pressure ratio are being investigated to increase fuel efficiency and reduce airport noise levels. In a joint supersonic cruise propulsion program with industry, the critical environmental concerns of emissions and community noise are being addressed. NASA is also providing key technologies for the National Aerospaceplane, and is studying propulsion systems that provide the capability for aircraft to accelerate to and cruise in the Mach 4-6 speed range. The combination of fundamental, component and focused technology development underway at NASA will make possible dramatic advances in aeropropulsion efficiency and environmental compatibility for future aeronautical vehicles.				
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